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ESL-TR-84-22

AD-A145 087

Evaluation of Projectile Impact on Earth-Covered Structures

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ENGINEERING & RESEARCH DIVISION
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JUNE 1984

FINAL REPORT
1 JUNE 1983 - 1 AUGUST 1983

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS: N/A

2a. SECURITY CLASSIFICATION AUTHORITY: N/A

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

3. DISTRIBUTION/AVAILABILITY OF REPORT: Distribution Unlimited/Available for Public Release

4. PERFORMING ORGANIZATION REPORT NUMBER(S): ESL-TR-84-22

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: Air Force Engineering and Services Laboratory

6b. OFFICE SYMBOL *(If applicable)*: AFESC/RDCS

7a. NAME OF MONITORING ORGANIZATION:

6c. ADDRESS *(City, State and ZIP Code)*: Tyndall AFB Florida 32403

7b. ADDRESS *(City, State and ZIP Code)*:

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Air Force Office of Scientific Research

8b. OFFICE SYMBOL *(If applicable)*: AFOSR

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F49620-82-C-0035

8c. ADDRESS *(City, State and ZIP Code)*: Bolling AFB, DC 20332

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
62601F	2673	00	25

11. TITLE *(Include Security Classification)*: Evaluation of Projectile Impact on Earth-Covered Structures

12. PERSONAL AUTHOR(S): Logan, Daryl L.

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM 83 Jun 1 TO 83 Aug 1

14. DATE OF REPORT *(Yr., Mo., Day)*: 84 Jun

15. PAGE COUNT:

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB. GR.
13	13	
19	04	

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*: Penetration, Impact, Projectile, Spall, Earth-Covered, Perforation

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This report investigates the capability of earth-covered reinforced concrete structures to withstand the local response of impacting projectiles. Soil and concrete penetration, and thickness of concrete wall structures necessary to prevent perforation and scabbing, are predicted. ~~Also~~ examined ~~is~~ the influence of parameters soil penetrablity index, soil cover thickness, concrete compressive strength, concrete thickness and impact velocity on the local response. It is shown that for ranges of parameter values of interest soil penetrability index and soil cover thickness have the greatest influence on allowable missile weight (frontal pressure) at which incipient backface scabbing of the concrete wall occurs. The implementation of the results is demonstrated for data recorded from missile debris resulting from an actual aircraft shelter explosion experiment. The results indicate that nearly all data fall within safe limits of realizable parameter values. Implications for siting earth-covered structures with respect to aircraft structures are evident and suggestions for further research are indicated.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

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22c. OFFICE SYMBOL: AFESC/RDCS

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

PREFACE

This report was prepared by the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall AFB, Florida 32403 under the 1983 Summer Faculty Research Program sponsored by the Air Force Office of Scientific Research (AFOSR) and conducted by the Southeastern Center for Electric Engineering Education (SCEEE). The author, Dr. Daryl L. Logan, is an Associate Professor in the Civil Engineering Department at Rose-Hulman Institute of Technology, Terre Haute, Indiana.

This report investigates the capability of earth-covered reinforced concrete structures to withstand the local response of projectiles.

This study was done at the request of the Department of Defense Explosive Safety Board (DOESB) into the siting of hardened , semiburied facilities. This report covers work performed between 1 June 1983 and 1 August 1983. The AFESC/RDCS Project Officer was Capt. Paul L. Rosengren, Jr.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

A. BACKGROUND

The Air Force is concerned with the present siting restriction placed on all inhabited buildings, including semihardened facilities and earth-covered structures (Reference 1). Recent studies of the aftermath of aircraft shelter debris from bomb detonations within the aircraft shelter (Reference 2) have resulted in a 300-feet minimum spacing requirement between semihardened aircraft shelters and inhabited buildings, regardless of the protective capabilities of these inhabited buildings. This 300-foot siting requirement could be relaxed if tests or analysis were available to demonstrate the added protection from shelter debris provided by these protective structures.

This report is the result of a study to determine the capability of earth-covered structures to withstand the debris threat from a most probable detonation within a nearby aircraft shelter. The study concerned itself with the local response due to projectiles (missiles) impacting earth-covered structures.

B. OBJECTIVE:

The primary objective of this research effort was to examine survivability capabilities of earth-covered structures when such structures are subjected to debris missiles resulting from a bomb explosion within a nearby aircraft shelter.

Specific goals of the research were:

1. To determine appropriate procedures to adequately predict the local response of an earth-covered structure to missile impact.

2. To illustrate use of this procedure for an Air Force structure of interest subjected to missile debris of interest (Reference 2).

3. To recommend ways of increasing the survivability capabilities of the structure of interest.

SECTION II

METHODOLOGY

A. METHOD OF ANALYSIS AND EQUATIONS USED

This report will analyze the local response (as opposed to overall structural response) of an earth-covered structure to impact from aircraft shelter debris (missiles). The missiles considered are those created during an explosion occurring within an aircraft shelter as recorded in Reference 2. The local response refers to analysis of the earth-covered structure near the impact. The phenomena to be analyzed are penetration depth of a missile into the structure wall, perforation (a missile passing entirely through the wall thickness), and backface scabbing (scabbing of concrete off the inside face of the wall). The structures are assumed to be of reinforced concrete and to have an earth material overlying them.

Although analytical attempts have been under study (Reference 3) to predict local impact phenomena, these methods have not been fully developed. Therefore, this analysis is based on a series of recently assessed empirical equations (Equations (4) - (8)) which are used to predict penetration, perforation and backface scabbing as a missile impacts the soil cover associated with the structure.

The analysis procedure is as follows:

1. Calculate the depth of penetration, X_s, (in feet) of the tip of the missile into the earth overburden by

$$X_s = 0.53SN\left(\frac{W}{A}\right)^{1/2} \ln(1 + 2V^2 10^{-5}) \qquad (1)$$

where S = Soil penetrability index (soil constant)

N = missile nose-shape performance coefficient

W = missile weight, in pounds

A = missile impact cross-sectional area, in square inches and

V = missile impact velocity, in ft/sec

2. Calculate the residual velocity, Vc, (in ft/sec) by

$$V_c = V\left(1 - \frac{t_s}{\overline{X}_s}\right)^{1/2} \qquad (2)$$

where complete penetration of the overburden by the missile is assumed and

t_s = the soil overburden thickness, in units of feet.

3. Calculate the depth of penetration, x, (in inches) of the tip of the missile into the concrete wall as

$$x = 2d\sqrt{F} \quad ; \quad \text{for } \frac{x}{d} \leq 2.0 \qquad (3)$$

or $$x = d(F + 1) \quad ; \quad \text{for } \frac{x}{d} \geq 2.0 \qquad (3)$$

where $$F = \frac{180}{\sqrt{f'_c}} N_2 \left(\frac{E}{E_m}\right)^{1.25} \frac{W}{(d^{2.80})} \left(\frac{V_c}{1000}\right)^{1.80} \qquad (4)$$

and f'_c = concrete compressive strength, in psi

N_2 = missile nose shape coefficient

E = modulus of elasticity of missile material, in psi

E_m = modulus of elasticity of mild steel, in psi and

d = effective diameter of a missile, which has same contact area as that of actual contact area, in inches

4. Determine thickness, p, (in inches) of concrete wall to prevent perforation by

$$\frac{p}{d} = 1.32 + 1.24\left(\frac{x}{d}\right) ; \quad \text{for } 1.35 \leq \frac{x}{d} \leq 13.5 \qquad (5)$$

or $$\frac{p}{d} = 3.19\left(\frac{x}{d}\right) - 0.718\left(\frac{x}{d}\right)^2 \quad ; \quad \text{for } \frac{x}{d} \leq 1.35$$

5. Determine thickness, s, (in inches) of concrete wall to prevent backface scabbing by

$$\frac{s}{d} = 2.12 + 1.36\left(\frac{x}{d}\right) \; ; \text{ for } 0.65 \leq \frac{x}{d} \leq 11.75 \qquad (6)$$

or

$$\frac{s}{d} = 7.91\left(\frac{x}{d}\right) - 5.06\left(\frac{x}{d}\right)^2 \; ; \text{ for } \frac{x}{d} \leq 0.65$$

In Equations (1) through (6), the impact is assumed to be normal to the surface. Local impact is a function of many parameters including soil cover thickness, soil penetrability index, missile weight, missile contact, cross-sectional area, impact velocity, missile nose shape, and compressive strength of concrete structure.

B. SOLUTION PROCEDURE:

To satisfy the goals, critical frontal pressures, W/A, were determined for various distances (ranges) from the aircraft shelter for parameters of soil penetrability index, soil cover thickness, structure wall thickness and compressive strength, and missile impact velocity.

The solution procedure used was as follows. First, the initial velocity of a typical missile was calculated, using particle projectile motion equations (where the range of interest and an assumed launch angle were substituted into the equations). Range is defined to be the horizontal distance between where the missile is launched and where it lands. A representative missile contact area and nose shape coefficients ($N = 0.56$ and $N_2 = 0.72$) for blunt-ended missiles were assumed. Then the parametric study was undertaken, using variations in soil penetrability indices, soil cover, and concrete wall thickness and compressive strength. A trial-and-error process of selecting a missile weight and subsequent solution of Equations (1) - (6) was used. The process was stopped when a missile weight determined by the minimum concrete

thickness to prevent scabbing, from Equation (6), was obtained. That is, a weight resulting in an s, from Equation (6), equal to the concrete wall thickness was obtained. This weight is defined to be the critical weight resulting in incipient backface scabbing. To facilitate the parametric study, a FORTRAN computer program, based upon Equations (1) - (6), was written to determine the critical missile weight as well as missile penetration depth into the wall and minimum concrete thickness to prevent missile perforation.

SECTION III

NUMERICAL RESULTS

Numerical results are now presented for typical parameters of interest to the Air Force. Some of the values of parameters used include,

1. Soil penetrability indices (constants) given by

SOIL CONSTANT	TYPICAL SOIL DESCRIPTION
5.2	Clayey silt, silty clay, dense, hard, dry
7.0	Sand, loose to medium, moist
10.5	Clay, moist, stiff
30.0	Loose, moist topsoil with humus material, mostly sand and silt. Moist to wet clay, soft, low shear strength.
40.0	Clay, silty, wet

2. Soil cover thicknesses of 3, 4 and 5 feet.

3. Concrete wall thicknesses of 9 and 12 inches

4. Concrete compressive strengths of 4000 and 5500 pounds per square inch.

Equations (1) and (4) show that more meaningful results are obtained by expressing W and A as a single parameter. This possibility was verified as shown by Table 1 where the frontal pressure (W/A) at incipient scabbing for different cross-sectional areas at different ranges is given for values of $S = 10.5$, $t_s = 3$ ft, $f_c' = 5500$ psi and concrete thickness = 9 in.

TABLE 1. FRONTAL PRESSURE (W/A) AT INCIPIENT SCABBING FOR DIFFERENT CROSS-SECTIONAL AREAS

	FRONTAL PRESSURE (W/A)	
Range, R, FT.	$A = 1963$ IN^2	$A = 78.54$ IN^2
50	687.5	700.1
100	178.2	184.4
150	86.7	85.9
200	48.4	49.0
250	32.1	33.1
300	23.1	23.5

The ratio W/A is called frontal pressure. In this report critical frontal pressure is defined to be that frontal pressure causing incipient scabbing.

Figures 1 through 5 illustrate the influence of various parameters on critical frontal pressure. Throughout, the missile is assumed to be steel. Figure 1 shows critical frontal pressure, W/A, for various ranges, R, for different soil penetrability indices. (Actually $(W/A)^{1/2}$ is used to present the data in a more meaningful graphical form). The launch angle of the missile is 30 degrees from the horizontal, soil cover thickness is 3 feet and concrete wall thickness, t_c, is 9 inches. Figure 1 shows that, as soil penetrability index decreases, the critical frontal pressure increases. That is for a dense, hard, dry silty clay (S = 5.2), critical W/A is larger than for a loose to medium moist sand (S = 7.0). Comparisons of results for the soil descriptions corresponding to each S indicate that, in general, dense, hard, dry soils resist penetration noticeably better than loose, soft, wet soils. Further it can be observed that, as the range increases the critical W/A decreases. This is reasonable, based on the fact that it takes a larger initial velocity to project a missile for a longer range. The resulting impact velocity is equal to the initial velocity based on projectile motion equations.

Figure 2 shows the results of W/A for various R for different soil cover thicknesses, t_s for a given S and t_c. Here the greater t_s, the greater critical W/A. For S = 10.5, 4 feet of soil cover may increase the critical W/A by as much as 1.75 times compared to 3 feet of cover. Again W/A decreases with increasing R for reasons explained in the previous paragraph.

Figures 3 and 4 demonstrate critical W/A for various R for different concrete compressive strengths and concrete wall thicknesses, respectively. It can be observed that critical W/A are negligibly influenced by concrete compressive strength and wall thicknesses of usual interest.

Finally Figure 5 shows the influence of the missile is initial velocity of impact on the critical W/A at a range of 100 feet. As the initial velocity of impact increases the critical W/A decreases.

In summary, a parametric study, based on a series of empirical equations used to predict soil penetration, concrete penetration, perforation, and scabbing, was undertaken to determine the most important factors influencing local missile impact response for a typical Air Force earth-covered structure. For ranges of parameters of interest, it was determined that soil penetrability index and soil cover thickness have the greatest influence on allowable frontal pressures at which incipient scabbing occurs. Fortunately, these two parameters are quite easily controlled and their required values and achieved in a relatively economical fashion.

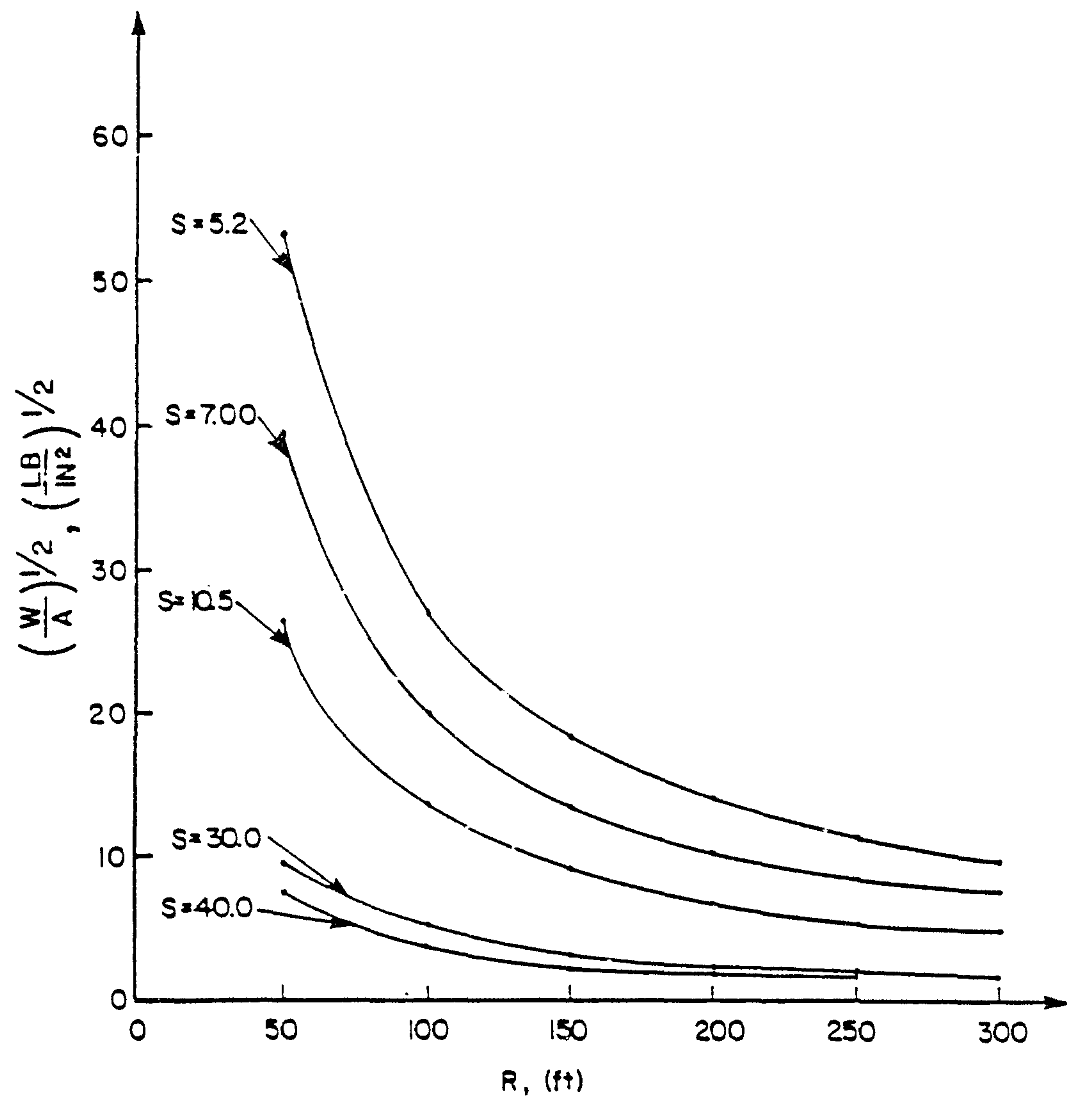

Figure 1. Range versus (frontal pressure)$^{1/2}$ at Incipient Scabbing for Different Soil Penetrability Indices (For t_s=3 ft, t_c=9 in, f_c' = 5500 psi)

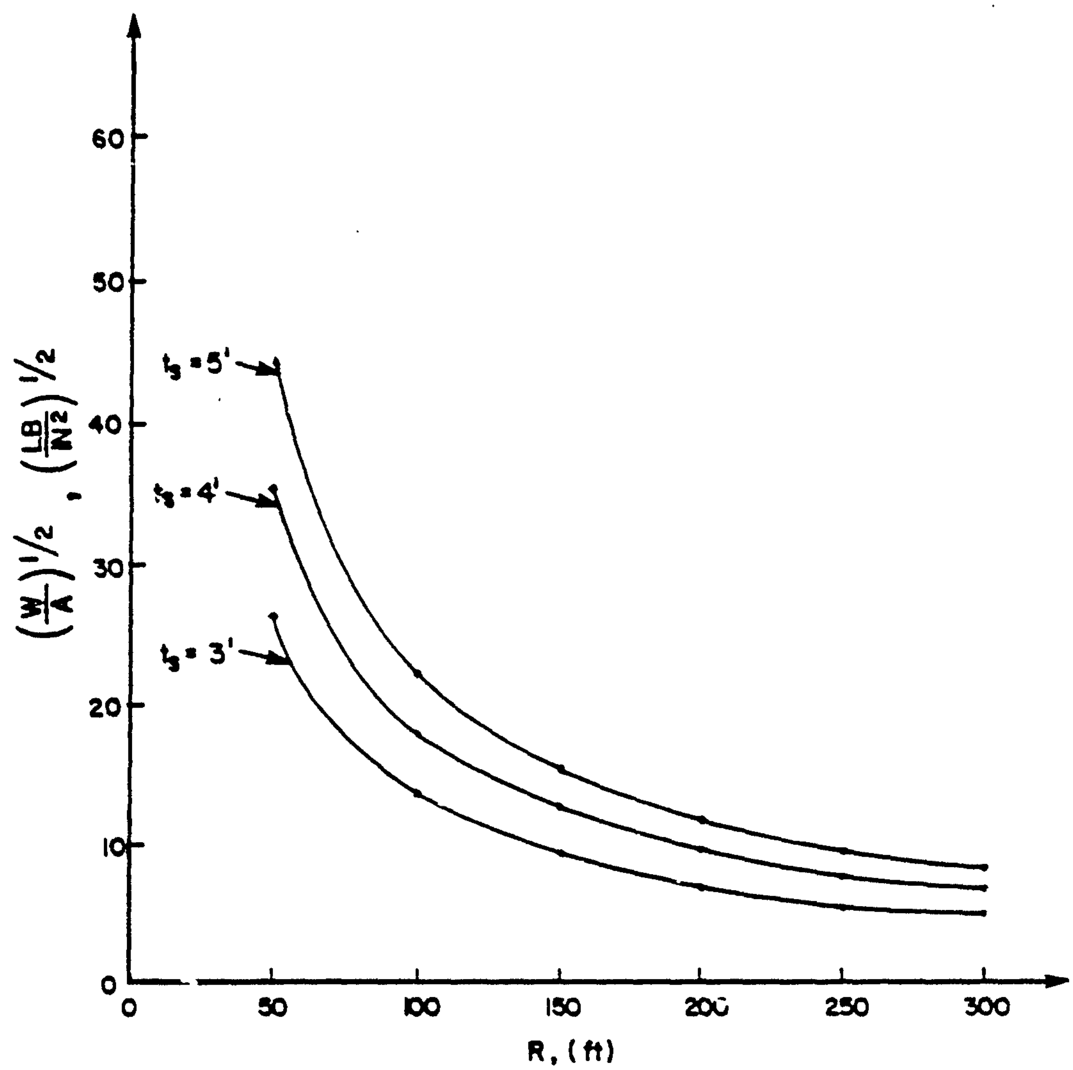

Figure 2. Range versus (frontal pressure)^{½} at Incipient Scabbing for Different Earth Cover Thicknesses (for S=10.5, t_c=9 in. f_c'=5500 psi)

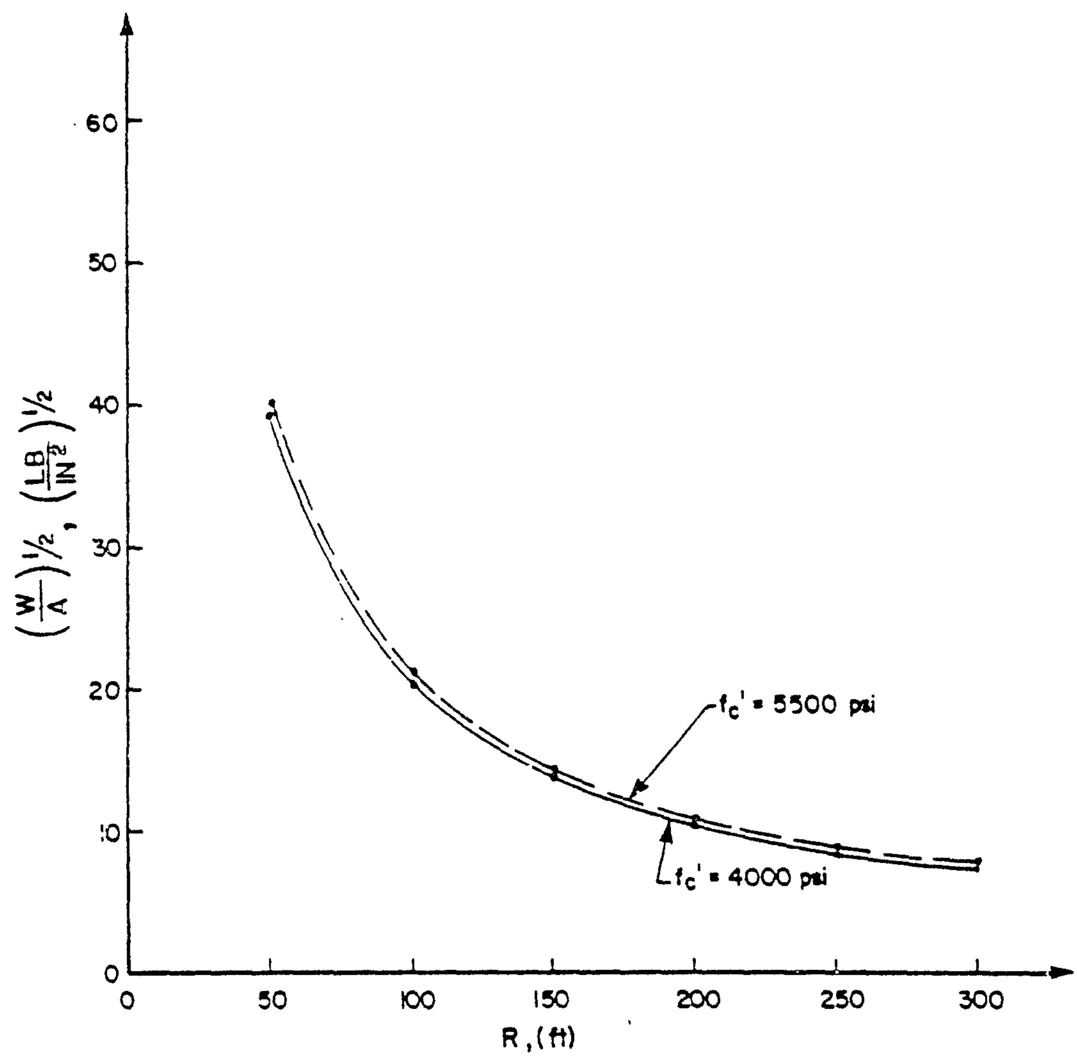

Figure 3. Range versus (frontal pressure)$^{\frac{1}{2}}$ at Incipient Scabbing for Different Concrete Compressive Strengths (For S=7.0, t_s=3 ft, t_c=9 in.)

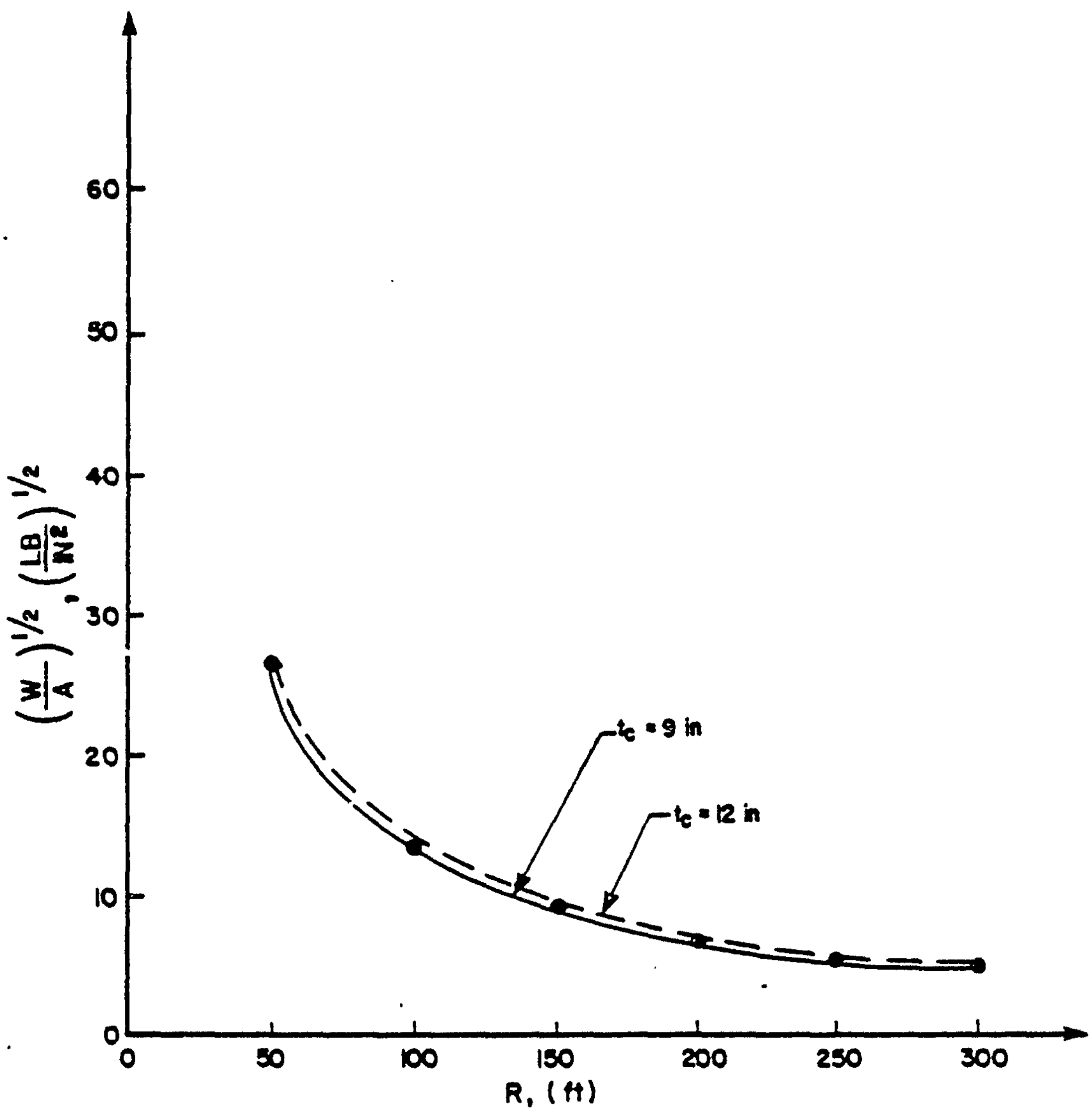

Figure 4. Range versus (frontal pressure)$^{\frac{1}{2}}$ at Incipient Scabbing for Different Concrete Wall Thicknesses (For S=10.5, t_s=3 ft, f_c'=5500 psi)

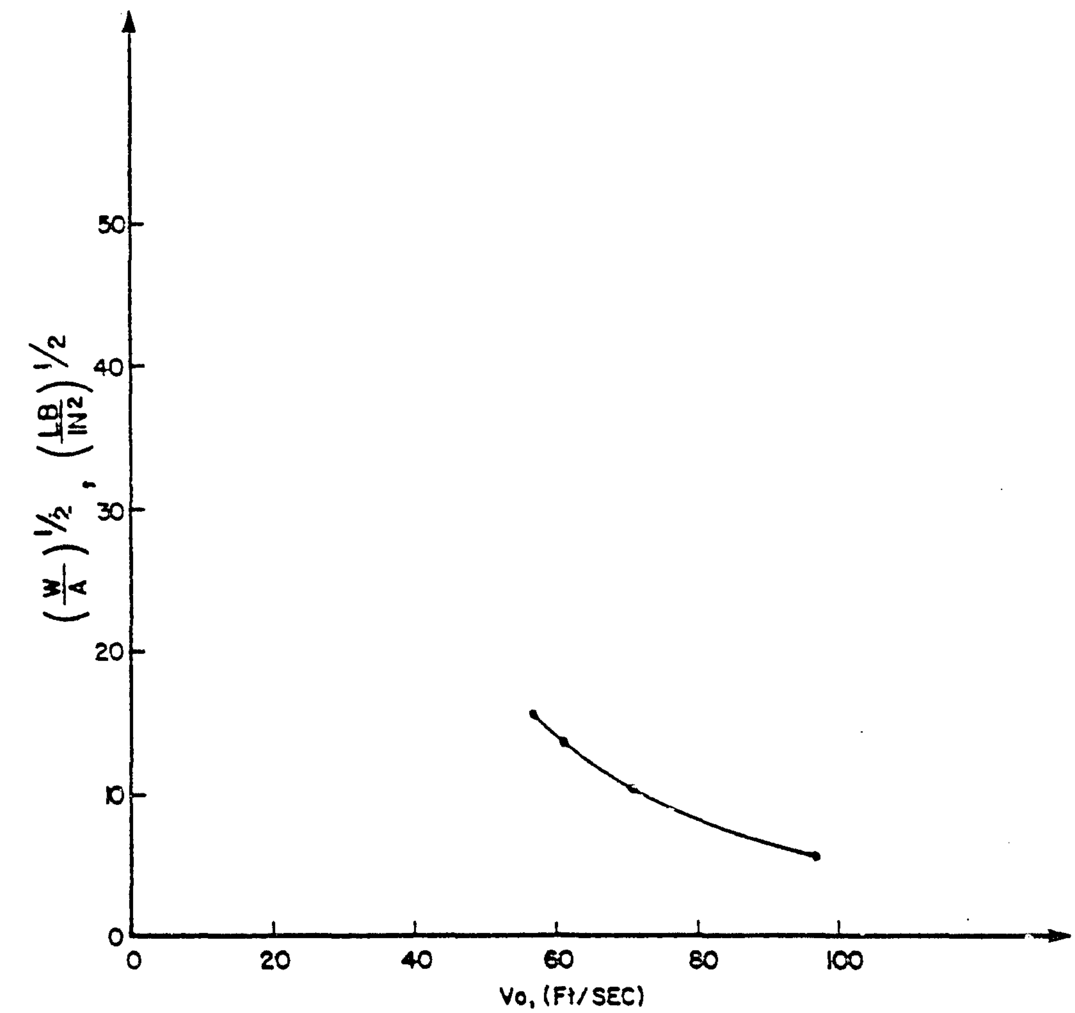

Figure 5. Impact Velocity versus (frontal pressure)$^{1/2}$ at Incipient Scabbing (For R=100 ft, S=10.5, t_s=3 ft, t_c=9 in, f'_c=5500 psi)

SECTION IV

RECOMMENDATIONS

A. IMPLEMENTATION OF RESULTS

The results of this research have immediate application to a soil-concrete layered medium in predicting missile penetration into the medium and the associated concrete thickness needed to prevent backface scabbing and perforation. An example of a military application is for earth-covered concrete structures subjected to debris resulting from an aircraft shelter explosion (Reference 2). The implementation of results is demonstrated in Figure 6 where the large debris data from (Reference 2) is expressed as $(W/A)^{1/2}$ and plotted for their ranges. These results are compared to critical $(W/A)^{1/2}$ versus R for various soil penetrability indices for 3 feet of soil cover. Nearly all data fall within safe limits of realizable soil parameters. Implications for siting earth-covered structures with respect to aircraft shelters are indicated.

Another application would be to predict the depth of penetration (or the burster layer thickness necessary to "catch" a bomb) into a concrete burster layer from a bomb. This information is necessary to define the ground-shock load used for underground shelter design.

B. SUGGESTIONS FOR FOLLOW-ON-RESEARCH

This research was based on local response behavior from a missile impacting an earth-covered structure. The local response equations were computer-programmed in a user-friendly manner for a soil-concrete medium. To expand the use of these equations, the computer program should be made more versatile, including capability of analysis for any combination of different materials (applications for composite construction barriers such as

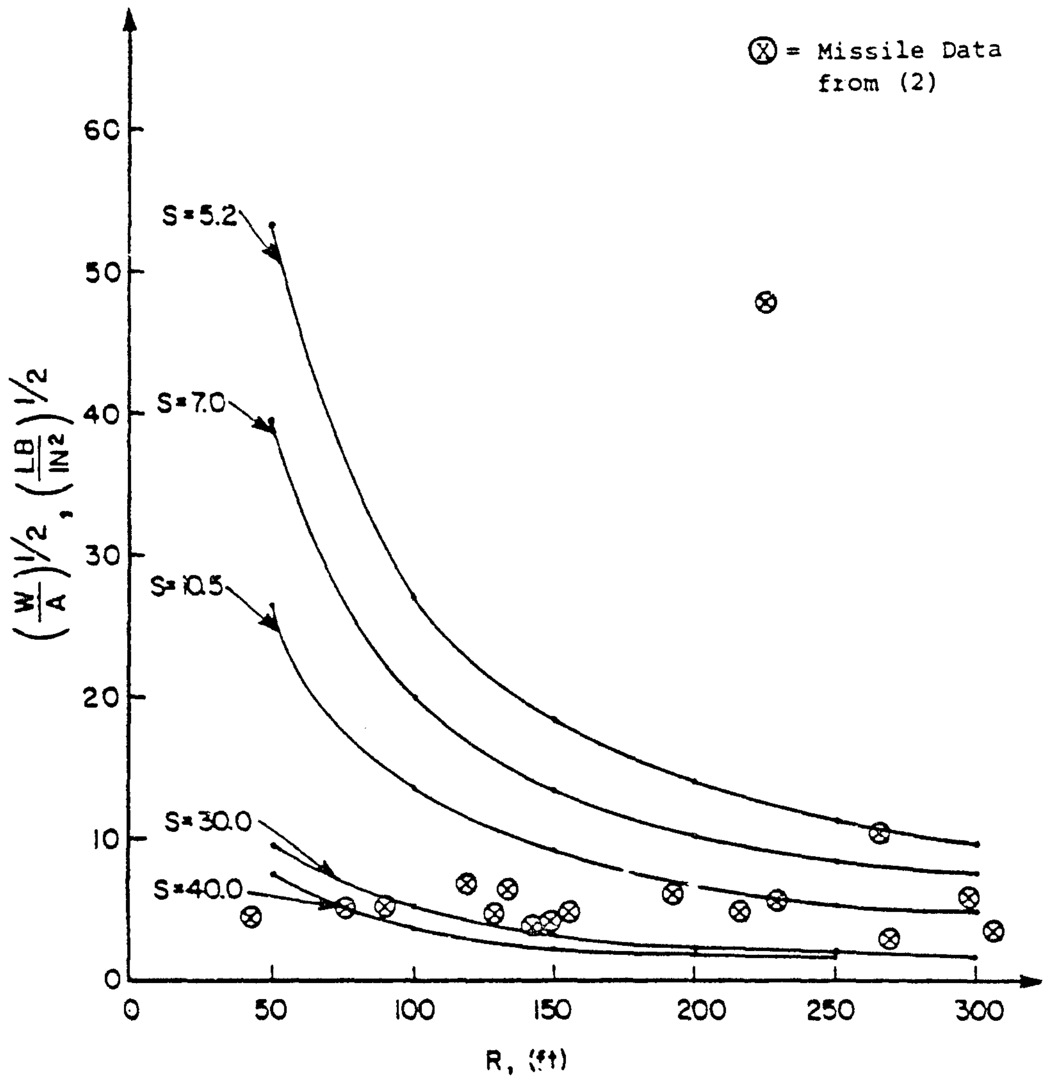

Figure 6. Comparison of Range versus (frontal pressure)$^{1/2}$ at Incipient Scabbing for Different Soil Penetrability Indices and Missile Data from (2) (For t_s=3 ft, t_c=9 in, f'_c =5500 psi)

concrete-sand-concrete and for soil-burster layer-soil penetration predictions) and capability to automatically converge to a critical weight. (This option would be obtainable by programming a numerical method into the existing program.)

The research should also be extended to utilize the results from the penetration equations in a model to predict overall structural response from missiles. This phase would include a method for determination of the force-time function(s) to be applied to the structure. This is a necessary phase of analysis in the determination of survivability of earth-covered systems. A finite element program, including the force-time function developed and soil interaction, would be used to complete the analysis.

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